ER-2 High Altitude Solar Cell Calibration Flights

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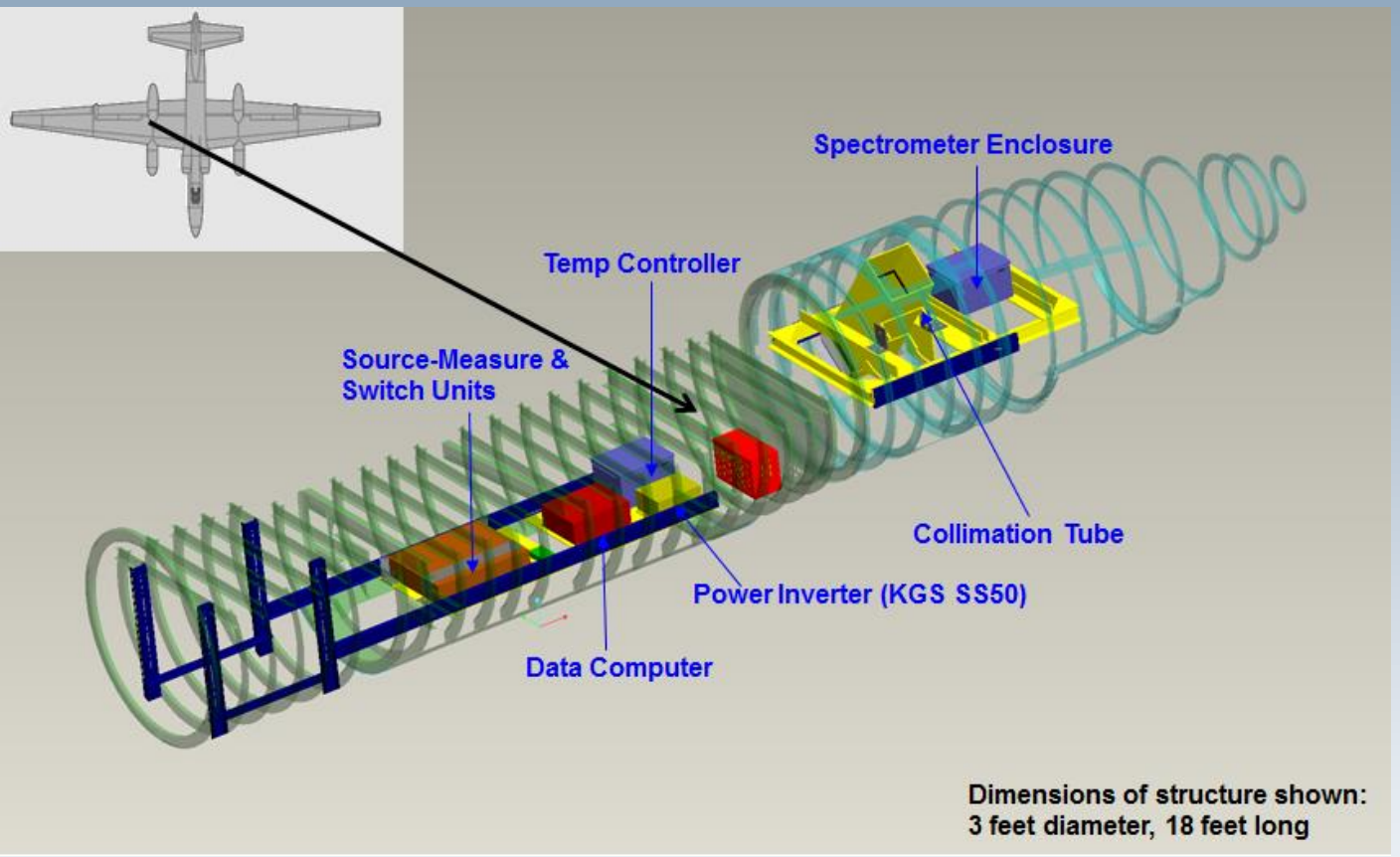
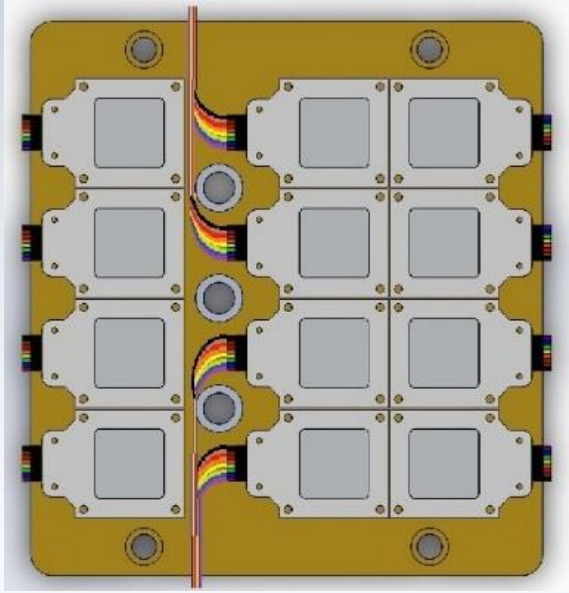
Test Platform Overview



Demonstrated Capabilities

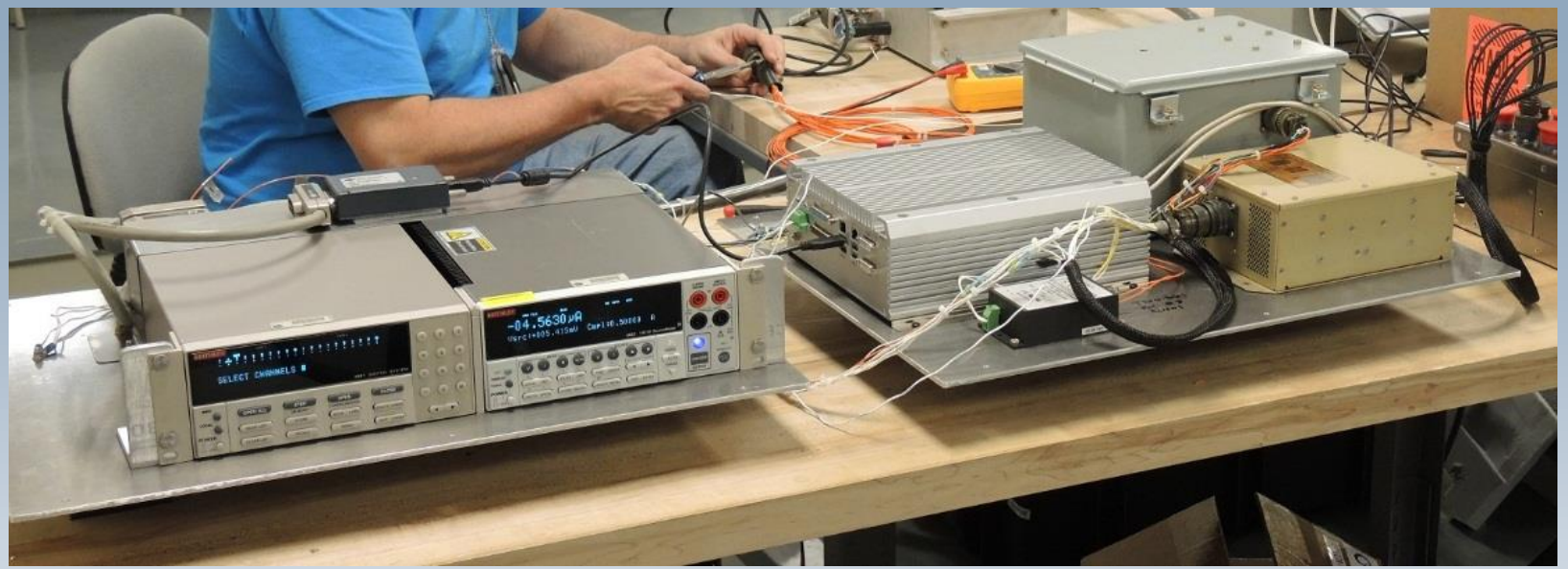
Altitude: 70,000ft+
Illuminated Area: 5.6 x 5.6 inches
Pointing Accuracy: <2° deviation
Temperature Control: (+/-) 0.5°C
Number of devices per flight: 12 Maximum
Cell Measurements: Isc, Voc, IV Curve
Fiber-optic Port for spectrometer or other sensor
Flight Season: April through September



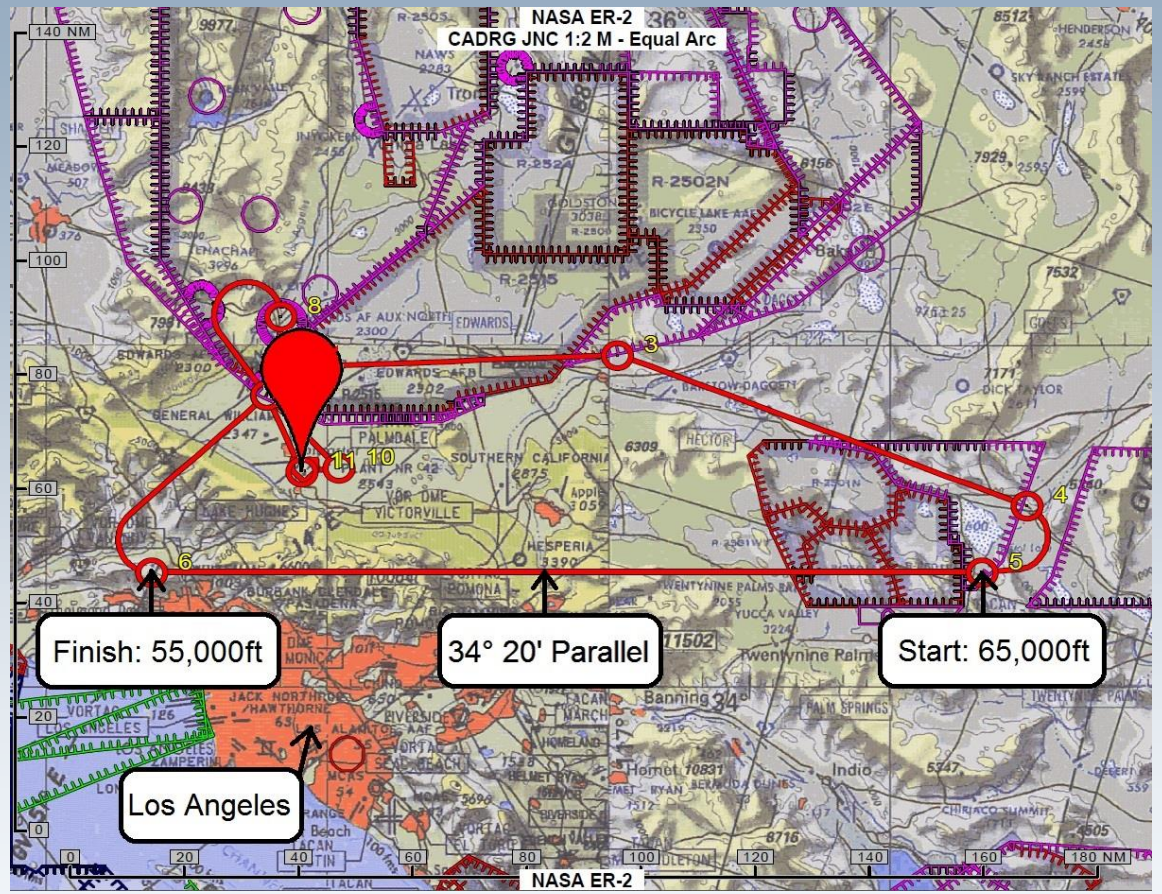
Instruments Flown

Keithley 2425 Source/Measure Unit
Ocean Optics HR2000+ Spectrometer
Ocean Optics NIRQuest NQ512-1.9 Spectrometer

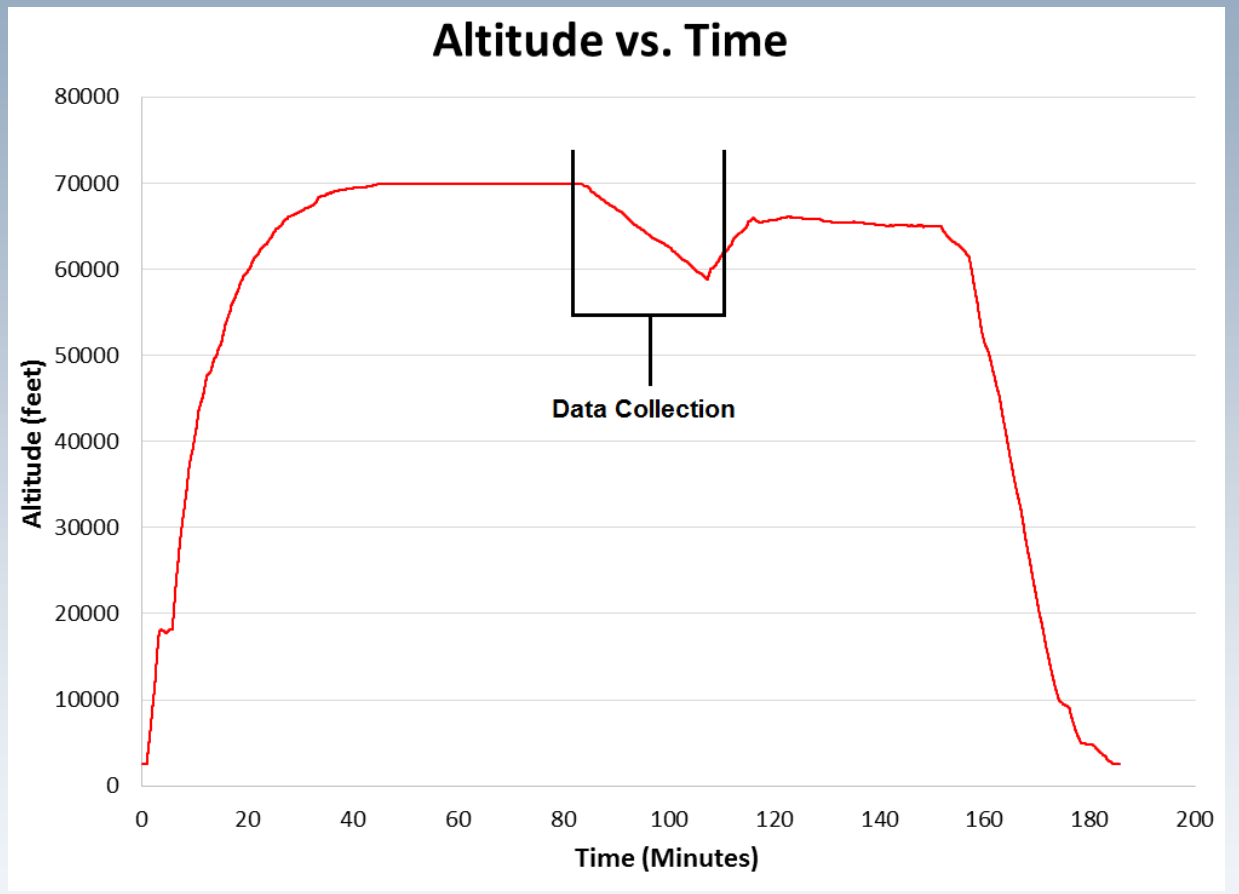
Equipment



Flight Profile



Ideal Regular Season Flight Path



Actual Altitude Profile

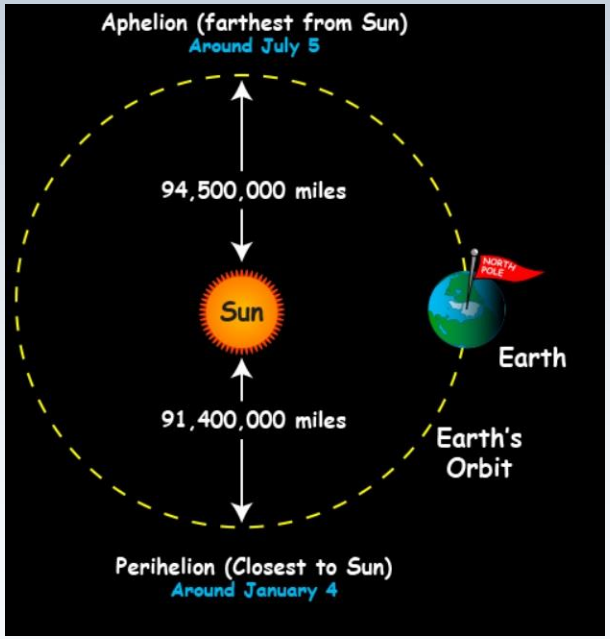
Data Correction Method

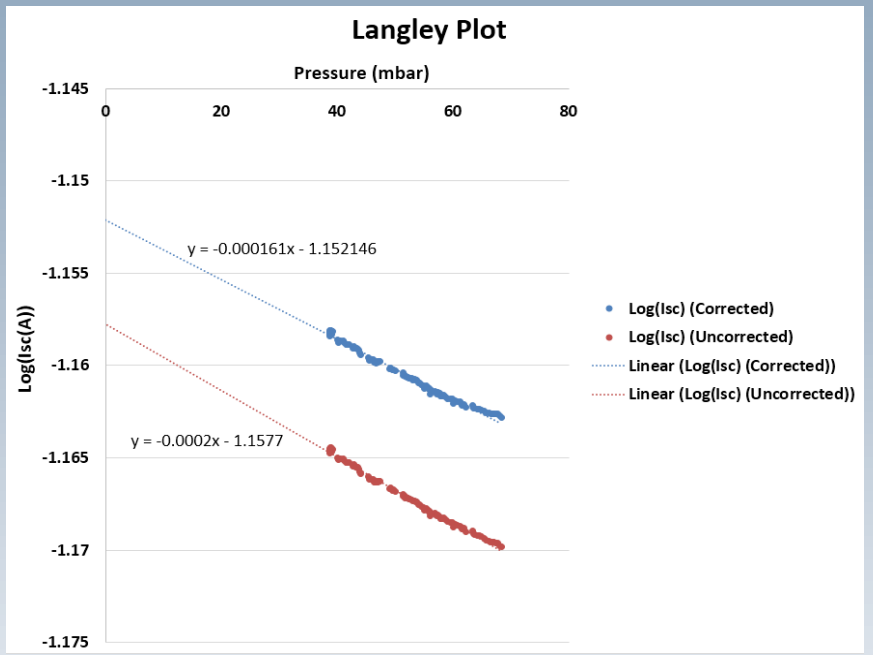
1.) Using a models for the AM0 spectrum, daily ozone distribution, and the measured cell EQE, the measured cell Isc vs. pressure data is corrected for residual ozone.

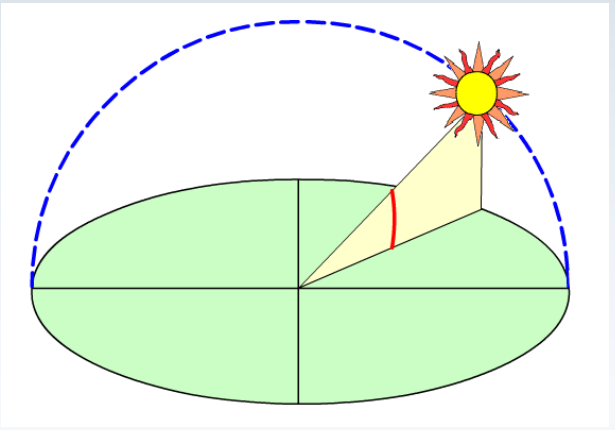
2.) Pressure is converted to airmass and a modified Langley plot method is used to extrapolate the zero pressure cell Isc.

3.) Corrections are made for earth-sun distance and solar elevation angle.

Umkehr Level	Ozone above top of level (DU) for specified total column
	290
Ground	290.00
0	275.53
1	264.86
2	251.72
3	224.65
4	163.79
5	90.39







Corrected Isc Results

Full Data Set

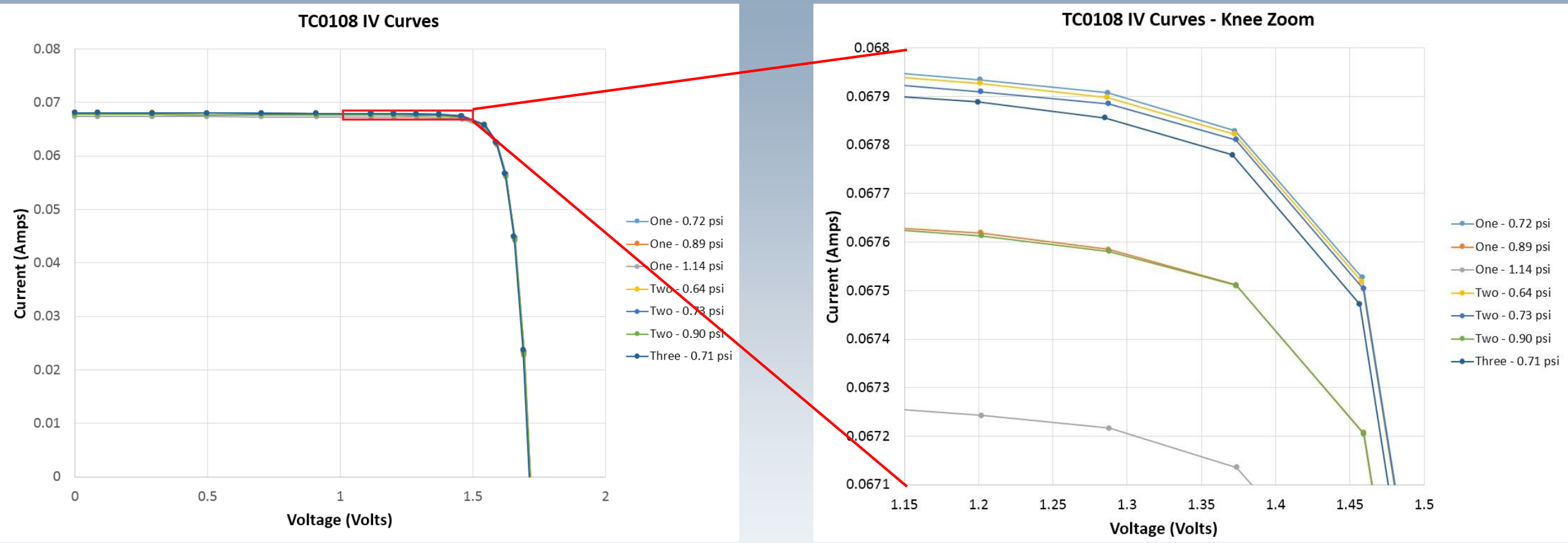
Cell	TC0108	MC0907	TC0109
Flight One	69.925	66.004	70.096
Flight Two	70.232	66.063	
Flight Three	70.289	65.990	
Average	70.149	66.019	70.096
Std Dev	0.196	0.039	
Covar %	0.279	0.059	
Learjet Value	70.510	66.230	70.51
Lear Variance (%)	0.512	0.319	0.587

<60mb Data Only

Cell	TC0108	MC0907	TC0109
Flight One	70.339	65.995	70.576
Flight Two	70.325	66.069	
Flight Three	70.289	65.990	
Average	70.318	66.018	70.576
Std Dev	0.026	0.044	
Covar %	0.037	0.067	
Learjet Value	70.51	66.23	70.51
Lear Variance (%)	0.27	0.32	-0.09

- Data shown for GRC 2x2cm ZTJ sub cells (two top cells and one middle)
- Ozone corrections based on established Learjet methods
- Further atmospheric correction methods are being investigated
  - SMARTS or other ozone models
  - Using only higher altitude data
  - Ozone correction coefficients using cell EQE data

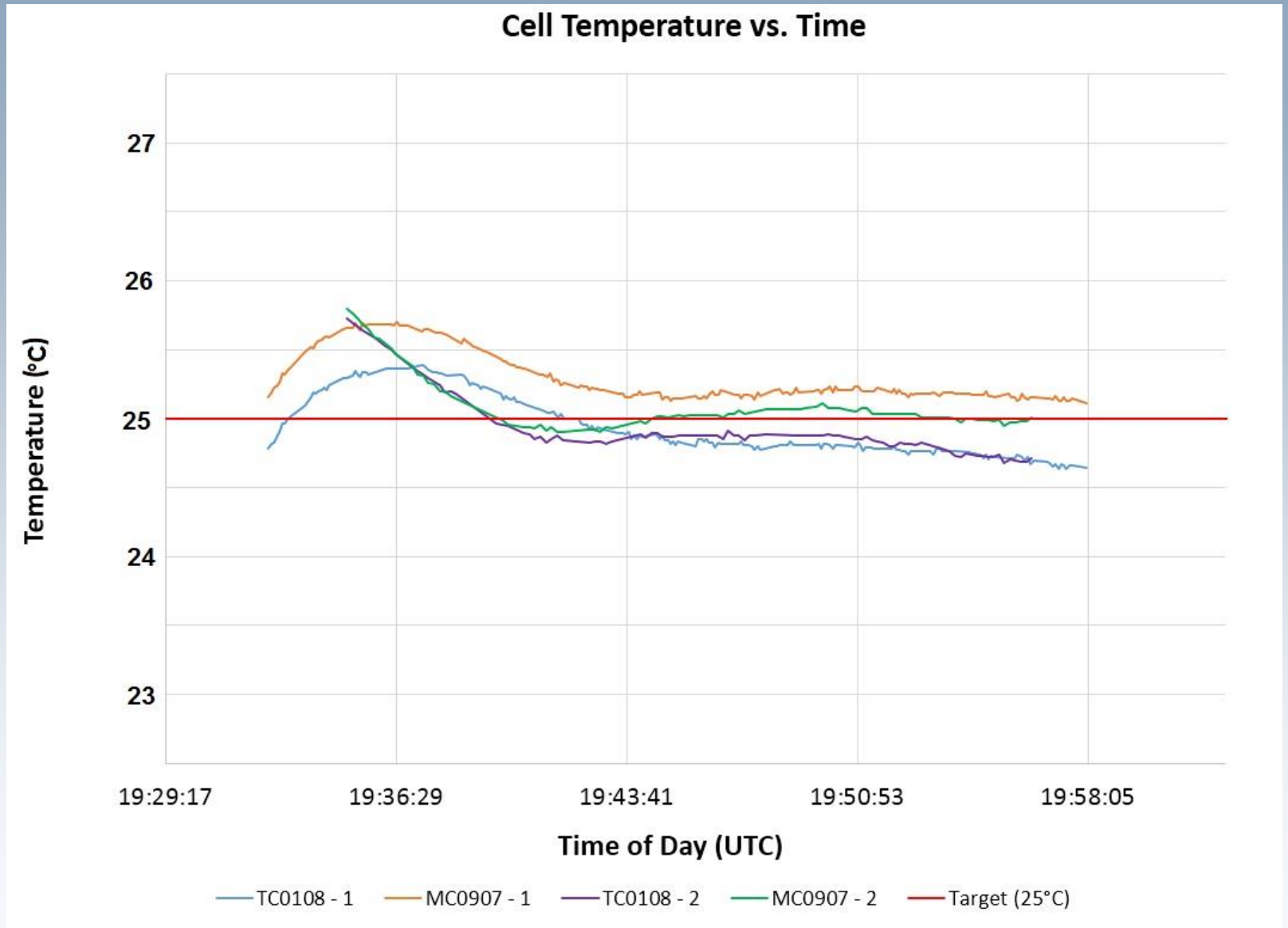
IV Curve Examples



IV Curves show good repeatability over multiple flights and a predictable change with pressure

Device Temperature Control

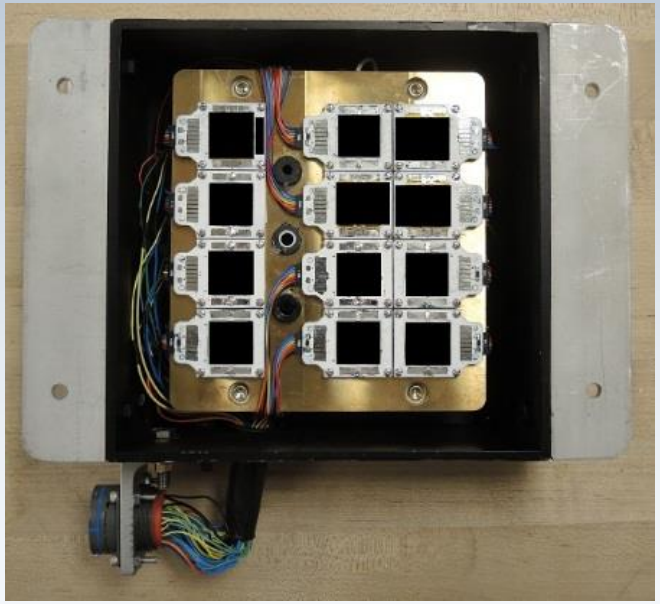
- Mounting Plate temperature is used for heater feedback control
- All cell temperatures are monitored independently using AD590 IC temperature transducers
- After a slight bump caused by initial solar illumination, all cell temperatures were maintained within approximately 0.25°C from the target of 25°C
- Variation of temperature for any individual cell was on the order of 0.1°C after the initial on-sun disturbance



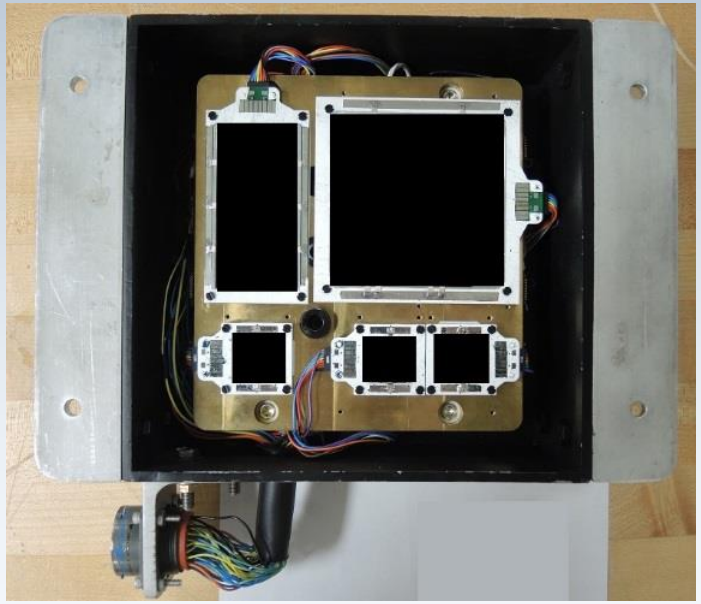
Sun Pointing

Summary ER-2 Campaigns

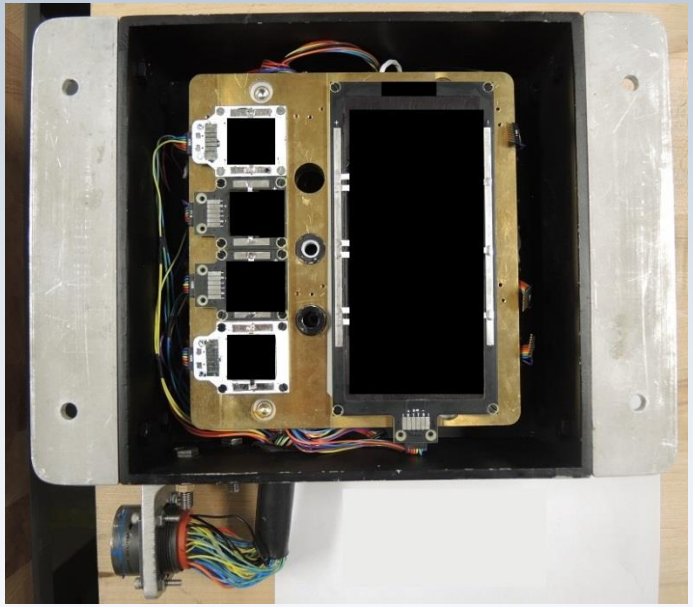
- Fifteen flights have been flown between October 8th 2014 and May 15th, 2017
- Data taken between 55,000 and 70,000 feet
- Around sixty unique devices tested
- Cell sizes flown include (in cm) 2x2, 4x8, 8x8 and 6x13
- Cell technologies include sub cells and full stack from 3-junction to 5-junction



Twelve 2x2cm cell configuration



4x8, 8x8 Configuration



6x13 Configuration

Summary ER-2 Campaigns

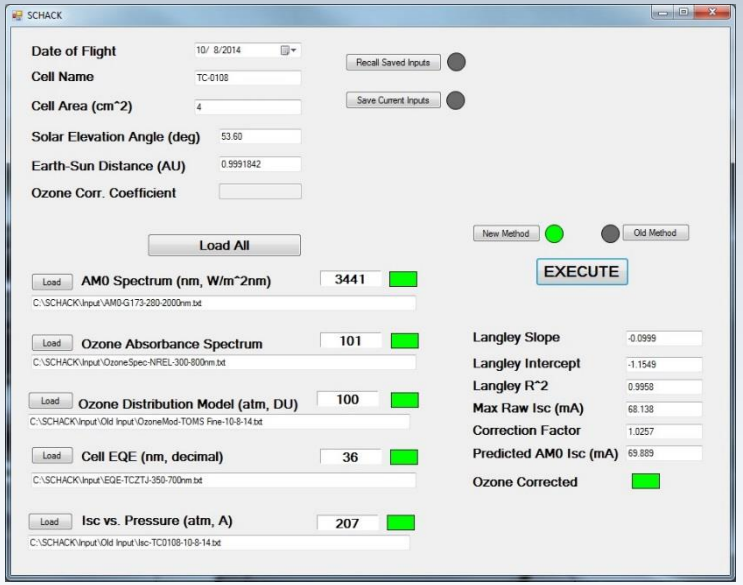
GRC Isc Historical Data, ZTJ Sub-Cells (mA)							
Flight	**Date**	**TC0108**	**TC0109**	**MC0907**	**MC0908**	**BC0902**	**BC0903**
1	10/8/2014	69.87		65.97			
2	10/10/2014	69.86		65.90			
3	10/14/2014	69.83		66.14			
4	3/26/2015		69.96	66.05			105.73
5	7/16/15		69.71	66.59			
6	7/21/15		69.84		66.25		107.96
7	7/22/15		69.74			105.10	
8	5/18/16		70.08				
9	5/23/16			66.99			
10	5/24/16						
11	4/12/17						106.25
12	4/14/17	69.81					
13	5/9/17					105.18	
14	5/11/17				66.20		
15	5/12/17						105.84
16	5/15/17				66.24		
Average		69.85	69.87	66.27	66.23	105.14	105.79
Std Dev.		0.023	0.155	0.429	0.025	0.055	1.033
Legacy Value		70.51	70.51	66.23	66.23	105.33	105.33
%Error		-0.93	-0.91	0.07	0.00	-0.18	0.43

Recent Updates

- Ground test stand was built to test PV instrument in a flight-like electrical configuration
- New wiring harnesses built by AFRC technicians were integrated into the instrument
- Software developed to automate and formalize process of AM0 Isc extrapolation (SCHACK)
- Collimation tube baffles redesigned to further eliminate glare
- 2017 season saw six flights with 28 unique cells flown

Test Stand and Electrical Simulator

New Wiring Harnesses



SCHACK Software

Summary of ER-2 Capability

- Flights can be conducted once every one to two days during a campaign
- Flight season runs from April through September
- Twelve 2x2cm cells can be flown per flight, or any other configuration that fits inside of the 14.2x14.2cm illuminated area
- This capacity could be doubled if the second ER-2 pod is used
- Data supplied includes Isc, Voc, IV curve, and cell temperature
- Other optical or atmospheric sensors can be flown as able

Questions